New Subsurface Signals

Introduction

A major obstacle to adaptive control of subsurface fractures, reactions and flow is our inability to clearly characterize and monitor critical subsurface features. Although the energy industry has developed sophisticated tools to characterize the subsurface using both surface and wellbore methods, an entirely new class of capabilities are needed to characterize fractures and associated processes at sufficiently high spatial resolution and over large enough volumes to guide subsurface operations. The challenge is complicated by the range of relevant scales and the coupled nature of relevant thermal-hydrological-mechanical-chemical (THMC) processes. The 'New Subsurface Signals' theme seeks to transform our ability to characterize subsurface systems by focusing on four areas of research: new signals, integration of multiple datasets, identification of critical system transitions, and automation. A focus is on co-characterization of physical, geochemical, and mechanical properties using multiple datasets and on leveraging advances in material science, nano-manufacturing, and high-performance computing. Success in addressing this challenge is needed to master the subsurface, enabling efficient and environmentally sound subsurface energy production and energy waste storage.

Knowledge Gaps and Proposed Research

New sensors and approaches for monitoring fracture evolution, reactions and flow. This topic focuses on developing new approaches to remotely characterize fracture distribution and behavior in-situ as well as associated flow and reactions. Development of both new sensors and time-lapse monitoring approaches are critical for meeting this objective. Advances in material science and manufacturing, especially nano-manufacturing, offer an exciting opportunity for development of next generation sensors that are cheap, small and high-performance. Such sensors could facilitate widespread deployment within a reservoir and lead to the data redundancy needed for vastly improved characterization of subsurface geochemical, hydrological, and mechanical properties. New geochemical monitoring approaches could include pH-, and Eh-sensitive tracer chemicals, inert gas-cocktail injected tracers, isotopic approaches and dye molecule-coated nanoparticles. The illumination of fractures and reactions could be greatly improved through the development of geophysically-detectable nano-injectates, which could be deployed as tracers, proppants, stimulation fluids and remotely monitored using time-lapse geophysical methods. Manipulation of borehole pressures and associated monitoring of induced resonant modes could aid in the quantification of fracture distributions. Advances in field-deployable lasers and fiber optics enable the development of new *in situ* sensing, including spectroscopic techniques to map wellbore chemistry with sufficient cm-scale resolution to resolve mineralogic composition within fractures.

In combination with new sensors, early research is indicating the potential of using repeated (time-lapse) surveys to highlight subsurface fracture evolution and flow. New avenues include the use of multiple time-lapse geophysical datasets and the development of time-lapse geochemical and geomechanical sensing approaches. Examples include: joint use of time-lapse acoustic emission, seismic and/or electromagnetic datasets to image fracture evolution; strain using borehole tiltmeters or surface measurements; fiber optic technologies for quantifying fracture dynamics; the use of trace chemical constituents and isotopes in produced fluids to infer changes in fracture density or spacing; and time-lapse geophysical methods to remotely quantify subsurface geochemical changes. Significant research is needed to fully explore the potential of these methods and to develop field-deployable techniques.

Next generation integration approaches. Imaging relies on multiple techniques to reveal the structure and composition of the subsurface. The next step is to combine measurements and models in a rigorous manner to simultaneously estimate subsurface properties of interest and associated parameter uncertainty. While methods for joint inversion of geophysical and hydrological datasets have been developed to characterize subsurface systems, several significant research gaps exist. New methods are needed that also consider incorporation of rich geomechanical and geochemical information within inversion procedures. Especially critical is the development of hierarchical and dynamic inversion approaches that consider the multi-scale, coupled and temporal nature of subsurface processes and datasets as well as information about antecedent conditions. Stochastic approaches offer an avenue for tackling these problems. These techniques are flexible and robust; can incorporate multiple types of data, petrophysical relationships and process models; and can provide realistic error estimates. A benefit of advanced uncertainty techniques comes from determining the covariance of measured parameters, which can lead to a better physical understanding of coupled processes as well as indicate which parameters are most valuable under specific conditions. For problems that require concurrent modeling of complex phenomena (such as of fluid flow, reactions and wave propagation) co-development of new inversion approaches with hardware/software could greatly improve computational feasibility, as could development of reduced order solutions. Finally, new techniques are needed to quantify the value of derived information, which can in turn be used to guide the development of optimized and cost-effective sensing suites.

Diagnostic signatures of critical transitions. The goal of research in this topic is the identification of signatures that are diagnostic of critical thresholds, where system behavior is dramatically different from previous conditions. Examples of critical transitions relevant for sustainable energy production and waste storage include the breaching of carbon sequestration caprock, the connection of hydraulically-induced fractures with an existing fault, wellbore integrity failures, or the influence of abrupt precipitation and dissolution processes on fluid flow. Most characterization approaches typically focus on quantification of a single subsurface property or state (such as permeability or gas saturation); multiple approaches are commonly used together to characterize different aspects of a single system as described above. In contrast, research in this topic seeks to identify an *integrated* signature, where integrated implies the combined use of a variety of subsurface signals to diagnose abrupt changes in any subset of THMC processes associated with step changes in system behavior. Using laboratory and field data collected during abrupt transitions in subsurface system behavior; physics-based as well as complexity-based (e.g., graph theory, pattern and fuzzy) approaches could be advanced to identify diagnostic signatures of critical system transitions using multiple datasets. Knowledge of integrated diagnostic signatures could pave the way for research focused on identifying precursors leading to critical transformations and the development of new sensor suites particularly optimized for early detection of such thresholds.

Autonomous acquisition, processing, and assimilation. Although a few wellbore measurements provide near real time information about drilling and other operations, the acquisition, inversion and interpretation of advanced field (geochemical, hydrological, geophysical, geomechanical) datasets and their automatic incorporation (or assimilation) into predictive reservoir models requires months to perform. This delay inhibits use of the rich information to guide adaptive operations of energy production or waste storage. The development of autonomous acquisition, processes and assimilation approaches, is critical for adaptive control of subsurface systems and inextricably linked (as input) to the 'fit for purpose simulation capabilities' theme. Research associated with advancing autonomous analytics blends systems engineering, computational and subsurface expertise. New acquisition software will be needed to autonomously trigger and co-acquire data from multiple sensors and to stream those datasets to computational centers. Data management, processing and visualization workflows and tools are needed that are capable of handling large and heterogeneous datasets and of performing real-time quality control steps in a manner performed today by subsurface scientists. Inversion approaches, such as those described above, could be automated to allow estimation of key parameters or states using the acquired field datasets. Approaches to assimilate direct measurements and inversion results into THMC models will be needed to guide 'adaptive control' of subsurface fractures, flow and reactions.